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The Power Factor

The advantages of improving the equipment and system power factor are not as obvious as the advantages of improving the kilowatt power consumption. Improvement in the plant power factor can result in savings in kilowatt-hour power consumption due to lower distribution and transformer losses and, in many cases, a substantial reduction in the energy demand charge.

4.1 WHAT IS THE POWER FACTOR?

Traditionally, power factor has been defined as the ratio of the kilowatts of power divided by the kilovolt-amperes drawn by a load or system, or the cosine of the electrical angle between the kilowatts and kilovolt-amperes. However, this definition of power factor is valid only if the voltages and currents are sinusoidal. When the voltages and/or currents are nonsinusoidal, the power factor is reduced as a result of voltage and current harmonics in the system.

Therefore, the discussion of power factor will be considered for the two categories, i.e., systems in which the voltages and currents are substantially sinusoidal and systems in which the voltages and currents are nonsinusoidal as a result of nonlinear loads.

4.2 THE POWER FACTOR IN SINUSOIDAL SYSTEMS

The line current drawn by induction motors, transformers, and other inductive devices consists of two components: the magnetizing current and the power-producing current.

The magnetizing current is that current required to produce the magnetic flux in the machine. This component of current creates a reactive power requirement that is measured in kilovolt-amperes reactive (kilovars, kvar). The power-producing current is the current that reacts with the magnetic flux to produce the output torque of the machine and to satisfy the equation

$$T = K\Phi I$$

where

T = output torque

Φ = net flux in the air gap as a result of the magnetizing current

I = power-producing current

K = output coefficient for a particular machine

The power-producing current creates the load power requirement measured in kilowatts (kW). The magnetizing current and magnetic flux are relatively constant at constant voltage. However, the power-producing current is proportional to the load torque required.

The total line current drawn by an induction motor is the vector sum of the magnetizing current and the power-producing current. For three-phase motors, the apparent power, or kilovolt-ampere (kVA) input to the motor, is

$$\text{kVA} = \frac{I_L V_L \sqrt{3}}{1000}$$

where

I_L = total line current

V_L = line-to-line voltage

The vector relationship between the line current I_L and the reactive component I_x and load component I_p currents can be expressed by a vector diagram, as shown in Fig. 4.1, where the line current I_L is the vector sum of two components. The power factor is then the cosine of the electrical angle θ between the line current and phase voltage.

This vector relationship can also be expressed in terms of the components of the total kilovolt-ampere input, as shown in Fig. 4.2. Again, the power factor is the cosine of the angle θ between the total kilovolt-ampere and kilowatt inputs to the motor. The kilovolt-ampere input to the motor consists of two components: load power, i.e., kilowatts, and reactive power, i.e., kilovars.

The system power factor can be determined by a power factor meter reading or by the input power (kW), line voltage, and line current readings. Thus,

$$\text{Power factor} = \frac{\text{kW}}{\text{kVA}}$$

where

$$\text{kVA} = \frac{I_L V_L \sqrt{3}}{1000}$$

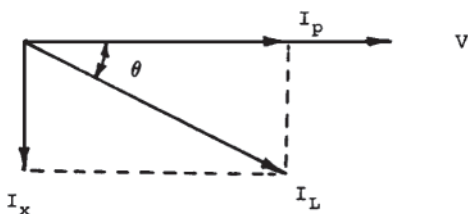


FIGURE 4.1 Vector diagram of load current for one phase of the motor.

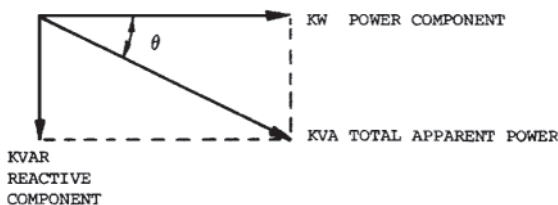


FIGURE 4.2 Vector diagram of power input without a power factor correction.

Then kvar is

$$\text{kvar} = \sqrt{(\text{kVA})^2 - (\text{kW})^2}$$

An inspection of the kilovolt-ampere input diagram shows that the larger the reactive kilovar, the lower the power factor and the larger the kilovolt-ampere for a given kilowatt input.

4.3 WHY RAISE THE POWER FACTOR?

A low power factor causes poor system efficiency. The total apparent power must be supplied by the electric utility. With a low power factor, or a high-kilovar component, additional generating losses occur throughout the system. Figures 4.3 and 4.4 illustrate the effect of the power factor on generator and transformer capacity. To discourage low-power factor loads, most utilities impose some form of penalty or charge in their electric power rate structure for a low power factor.

When the power factor is improved by installing power capacitors or synchronous motors, several savings are made:

1. A high power factor eliminates the utility penalty charge. This charge may be a separate charge for a low power factor or an adjustment to the kilowatt demand charge.

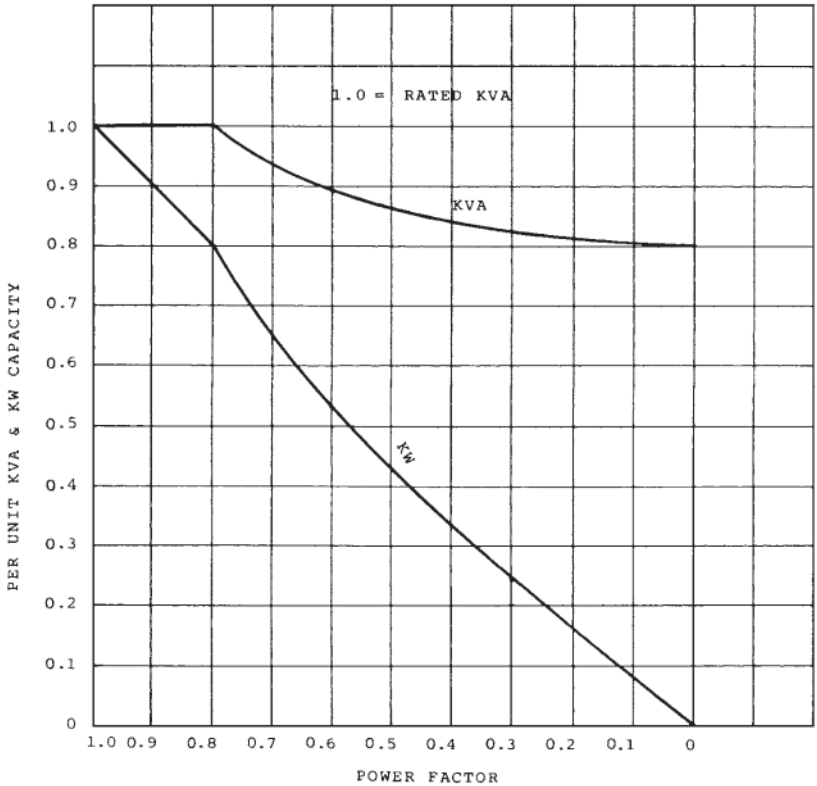


FIGURE 4.3 Power factor effect on generator capacity.

2. A high power factor reduces the load on transformers and distribution equipment.
3. A high power factor decreases the I^2R losses in transformers, distribution cable, and other equipment, resulting in a direct saving of kilowatt-hour power consumption.
4. A high power factor helps stabilize the system voltage.

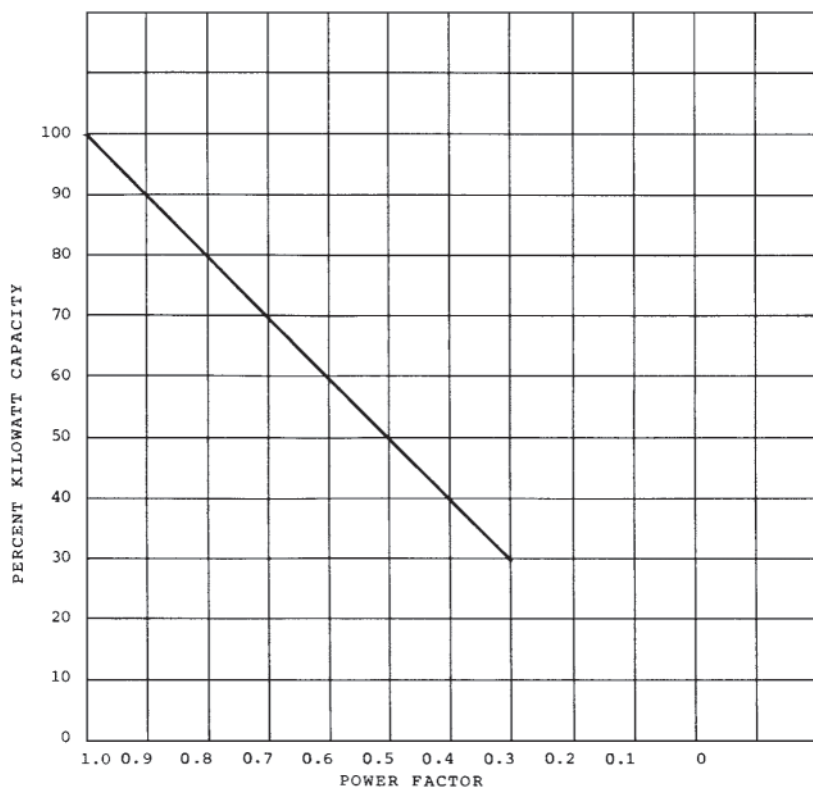


FIGURE 4.4 Power factor effect on transformer capacity.

4.4 HOW TO IMPROVE THE POWER FACTOR

To improve the power factor for a given load, the reactive load component (kvar) must be reduced. This component of reactive power lags the power component (kW input) by 90 electrical degrees, so that one way to reduce the effect of this component is to introduce a reactive power component that leads the power

component by 90 electrical degrees. This can be accomplished by the use of a power capacitor, as illustrated in the power diagram in Fig. 4.5, resulting in a net decrease in the angle θ or an increase in the power factor.

Several methods are used to improve the power factor in a system installation. One method that can be employed in large systems is to use synchronous motors to drive low-speed loads that require continuous operation. A typical application for a synchronous motor is driving a low-speed air compressor, which provides process compressed air for the plant. The synchronous motor is adjusted to operate at a leading power factor and thus provide leading kilovars to offset the lagging kilovar of inductive-type loads such as induction motors.

Synchronous motors are usually designed to operate at an 80% leading power factor and to draw current that leads the line voltage rather than lags it, as is the case with induction motors and transformers. For example, consider a load of 2000 kW at a 70% lagging power factor. The utilization of a 200-hp synchronous motor operating at an 80% leading power factor will increase the overall system power factor from 70% lagging to 85% lagging.

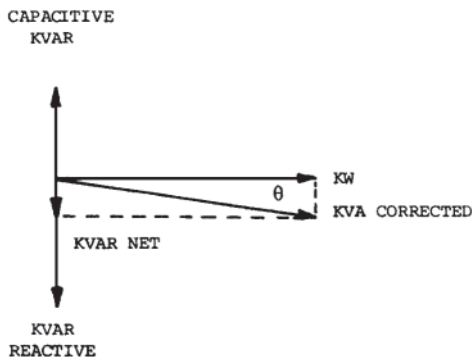


FIGURE 4.5 Vector diagram of power input with a power factor correction.

The more popular method of improving the power factor on low-voltage distribution systems is to use power capacitors to supply the leading reactive power required. The amount and location of the corrective capacitance must be determined from a survey of the distribution system and the source of the low-power factor loads. In addition, the total initial cost and payback time of the capacitor installation must be considered.

To reduce the system losses, the power factor correction capacitors should be electrically located as close to the low-power factor loads as possible. In some cases, the capacitors can be located at a particular power feeder. In other cases, with large-horsepower motors, the capacitors can be connected as close to the motor terminals as possible. The power factor capacitors are connected across the power lines in parallel with the low-power factor load.

The number of kilovars of capacitors required depends on the power factor without correction and the desired corrected value of the power factor.

The power factor and kilovars without correction can be determined by measuring the power factor, line amperes, and line voltage at the point of correction. For a three-phase system,

$$\text{kVA input} = \frac{\text{line amperes} \times \text{line volts} \times \sqrt{3}}{1000}$$

$$\text{kW} = \text{kVA} \times \text{PF}$$

$$\text{kvar} = \sqrt{(\text{kVA})^2 - (\text{kW})^2}$$

Or the line kilowatts, line amperes, and line voltage can be measured. Then,

$$\text{kVA input} = \frac{\text{line amperes} \times \text{line volts} \times \sqrt{3}}{1000}$$

$$\text{PF} = \frac{\text{kW}}{\text{kVA}}$$

$$\text{kvar} = \sqrt{(\text{kVA})^2 - (\text{kW})^2}$$

The capacitive kilovars required to raise the system to the desired power factor can be calculated as follows:

$$\text{kvar capacitance} = \text{kvar load} - \sqrt{\frac{1 - \text{PF}^2}{\text{PF}^2}} (\text{kW load})^2$$

where PF is the desired power factor.

For example, consider a 1000-kW load with a 60% power factor, which one wishes to correct to 90%:

$$\text{kW load} = 1000$$

$$\text{kvar load} = \sqrt{\left(\frac{1000}{0.60}\right)^2 - 1000^2} = 1333 \text{ kvar}$$

$$\text{kvar capacitance} = 1333 - \sqrt{\frac{1 - (0.90)^2}{(0.90)^2}} 1000^2 = 849$$

Tables such as [Table 4.1](#) have been developed and are available from most power capacitor manufacturers to simplify this calculation. Table 4.1 provides a multiplier to be applied to the kilowatt load to determine the capacitive kilovars required to obtain the desired corrected power factor. Consider the same 1000-kW load with a 60% power factor which one wishes to correct to 90%. From Table 4.1, for the existing power factor (60%) and the corrected power factor (90%), the power factor correction factor is 0.849. Thus, the number of kilovars of capacitance required is $1000 \times 0.849 = 849 \text{ kvar}$.

Let us verify this calculation:

$$\text{Uncorrected kVA} = \frac{1000}{0.60} = 1667$$

$$\text{Uncorrected lagging kvar} = \sqrt{1667^2 - 1000^2} = 1333$$

$$\text{Correction capacitor kvar} = 849$$

$$\text{Net corrected lagging kvar} = 484$$

TABLE 4.1 Power Factor Correction Factors

Existing power factor, %	Corrected power factor			
	100%	95%	90%	85%
60	1.333	1.005	0.849	0.714
62	1.265	0.937	0.781	0.646
64	1.201	0.872	0.716	0.581
66	1.138	0.810	0.654	0.519
68	1.078	0.750	0.594	0.459
70	1.020	0.692	0.536	0.400
72	0.964	0.635	0.480	0.344
74	0.909	0.580	0.425	0.289
76	0.855	0.526	0.371	0.235
78	0.802	0.474	0.318	0.183
80	0.750	0.421	0.266	0.130
81	0.724	0.395	0.240	0.104
82	0.698	0.369	0.214	0.078
83	0.672	0.343	0.188	0.052
84	0.646	0.317	0.162	0.026
85	0.620	0.291	0.135	
86	0.593	0.265	0.109	
87	0.567	0.238	0.082	
88	0.540	0.211	0.055	
89	0.512	0.184	0.028	
90	0.484	0.156		
91	0.456	0.127		
92	0.426	0.097		
93	0.395	0.067		
94	0.363	0.034		
95	0.329			

$$\text{Corrected kVA} = \sqrt{1000^2 + 484^2} = 1111$$

$$\text{Corrected power factor} = \frac{1000}{1111} = 0.90$$

Over the years, there have been several guidelines used for the selection of induction motor power factor correction capacitors. Three of these guidelines are as follows:

1. Add corrective kilovars of capacitors equal to 90% of the motor no-load kilovolt-amperes.
2. Add corrective kilovars of capacitors equal to 100% of the motor no-load kilovolt-amperes.
3. Add corrective kilovars of capacitors equal to 50% of the motor full-load kilovolt-amperes.

Table 4.2 is a comparison of these methods of selecting correction capacitors for some typical four-pole, 1800-rpm induction motors.

TABLE 4.2 Comparison of Power Factor Correction Methods

Motor rating, hp	Initial PF	90% NL kVA		100% NL kVA		50% FL kVA	
		kvar	Corr. PF	kvar	Corr. PF	kvar	Corr. PF
Standard NEMA design B, 1800-rpm induction motors							
10	0.843	3.70	0.979	4.12	0.987	5.14	0.999
25	0.853	8.70	0.980	9.66	0.988	12.45	1.000
50	0.863	12.37	0.962	13.74	0.970	23.64	1.000
100	0.903	19.50	0.973	21.67	0.978	45.20	0.997L
200	0.905	37.34	0.973	41.49	0.978	89.24	0.997L
Energy-Efficient, 1800-rpm induction motors							
10	0.850	2.98	0.967	3.31	0.976	4.92	0.999
25	0.867	7.24	0.977	8.05	0.984	11.71	1.000
50	0.805	18.18	0.962	20.20	0.974	24.86	0.993
100	0.861	24.16	0.960	26.84	0.968	46.85	1.000
200	0.897	51.75	0.974	45.81	0.980	87.44	0.998L

The question is: What is a typical motor in regard to power factor? Figure 4.6 shows the variation in full-load power factor for standard four-pole, 1800-rpm induction motors. Figure 4.6 is based on published data from 10 electric motor manufacturers. The difference in the full-load power factor for a specific horsepower rating can vary by 5 to 15 points. Therefore, it is best to know the power factor information on the specific motors requiring power factor correction. The no-load methods of selecting correction capacitors are conservative and increase the corrected power factor to 95% or higher. However, the no-load information is not readily available. In contrast, the full-load power factor and efficiency are generally available either as published literature or on the motor nameplate. These data can be used to calculate the motor power factor and input kilowatt-amperes. The use of the 50% full-load kilowatt-amperes to determine the corrective kilovars generally results in a corrected

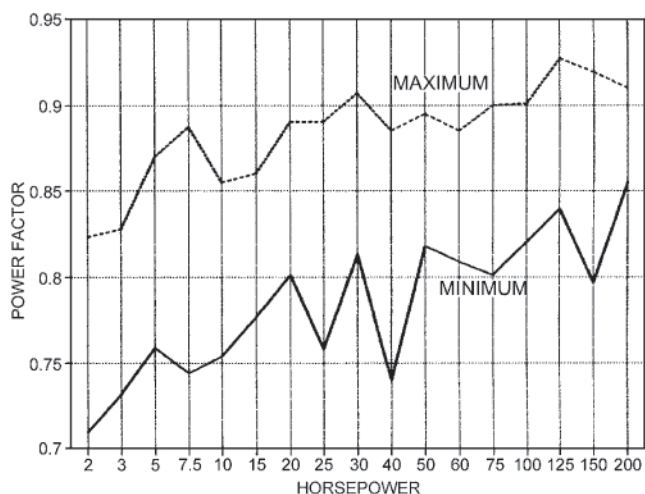


FIGURE 4.6 Power factor Nema design B, 1800-rpm induction motors.

power factor of 0.99 or better to a slightly leading power factor. This method should be used with caution if the motor is not operating at full rated load. Under partial-load conditions, the corrected power factor can be over 0.90 leading. The higher the horsepower of the motor, the more likely it is that the corrected power factor can be leading at partial loads. A partial motor load is not an unusual condition. Studies indicate that the average load on induction motors rated 125 hp and larger ranges from 50 to 85% of full-load rating. For 1800-rpm induction motors the power factor at 50% load is usually 0.07 to 0.14 points lower than the power factor at full load. If the capacitor correction is not used to supply kilovars for other uncorrected motors on the same circuit, a value lower than 50% of the full-load input kilovolt-amperes should be used for the correction kilovars.

In the application of power factor correction capacitors at the motor location, NEMA recommends the following procedure based on the published or nameplate data for the electric motor:

1. The approximately full-load power factor can be calculated from published or nameplate data as follows:

$$\text{PF} = \frac{431 \times \text{hp}}{E \times I \times \text{Eff}}$$

where

PF = per unit power factor at full load (per unit
PF = percent PF/100)

hp = rated horsepower

E = rated voltage

I = rated current

Eff = per unit nominal full-load efficiency from published
data or as marked on the motor nameplate (per unit
Eff = percent Eff/100)

2. For safety reasons, it is generally better to improve the power factor for multiple loads as a part of the plant distribution system. In those cases in which local codes or other circumstances require improving the power factor of an

individual motor, the kilovar rating of the improvement capacitor can be calculated as follows:

$$\text{kvar} = \frac{0.746 \times \text{hp}}{\text{Eff}} \left(\frac{\sqrt{1 - \text{PF}^2}}{\text{PF}} - \frac{\sqrt{1 - \text{PF}_i^2}}{\text{PF}_i} \right)$$

where

kvar = rating of a three-phase power factor improvement capacitor

PF_i = improved per unit power factor for the motor–capacitor combination

3. In some cases, it may be desirable to determine the resultant power factor PF_i, where the power factor improvement capacitor selected within the maximum safe value specified by the motor manufacturer is known. The resultant full-load power factor PF_i can be calculated from the following:

$$\text{PF}_i = \frac{1}{\sqrt{\{[(\sqrt{1 - \text{PF}^2})/\text{PF}] - [(\text{kvar} \times \text{Eff})/(0.746 \times \text{hp})]\}^2 + 1}}$$

Warning: In no case should power factor improvement capacitors be applied in ratings exceeding the maximum safe value specified by the motor manufacturer. Excessive improvement may cause overexcitation, resulting in high transient voltages, currents, and torques, which can increase safety hazards to personnel and cause possible damage to the motor or to the driven equipment. For additional information on safety considerations in the application of power factor improvement capacitors, see NEMA Publication No. MG2, *Safety Standard for Construction and Guide for Selection, Installation and Use of Electric Motors and Generators*.

The level to which the power factor should be improved depends on the economic payback in terms of the electric utility power factor penalty requirements and the system energy saved because of lower losses. In addition, the characteristic of the motor load must be considered. If the motor load is a cyclical load that varies from the rated load to a light load, the value of corrective kilovar capacitance should not result in a leading power factor at light loads.

To avoid this possibility, NEMA recommends that the maximum value of the corrective kilovars added be less than the motor no-load kilovar requirement by approximately 10%. Thus,

Maximum capacitor kvar for three-phase motors

$$= \frac{I_{NL} V \sqrt{3} \times 0.90}{1000}$$

$$= \frac{I_{NL} V}{642}$$

where

I_{NL} = motor no-load line current

V = motor line voltage

For example, consider a 50-hp, 1800-rpm induction motor operating on a 230-V, three-phase, 60-Hz power system. Table 4.3 shows the performance of this motor at various loads without power factor correction. Table 4.4 shows the full-load performance with various values of correction capacitor kilovars, including 100% of the no-load kilovolt-amperes (13.7 kvar) and

TABLE 4.3 Induction Motor Performance Without Power Factor Correction^a

Load	Line	Eff.	PF	kW input	kVA	kvar
Full load	118.7	0.915	0.862	40.8	47.3	24.0
3/4 load	89.4	0.922	0.852	30.3	35.6	18.6
1/2 load	64.8	0.920	0.785	20.3	25.8	16.0
1/4 load	44.1	0.887	0.598	10.5	17.6	14.1
No load	34.4	0.000	0.073	1.0	13.7	13.7

^a 50-hp, 1750-rpm, 230-V, three-phase, 60-Hz induction motor.

TABLE 4.4 Induction Motor and Capacitor Performance with Power Factor Correction at Full Load^a

Capacitor kvar	System line current	System kVA	System PF	Line loss reduction, %
0	118.7	47.3	0.862	0
8	109.9	43.8	0.931	14
12	106.7	42.5	0.959	19
13.7	105.5	42.0	0.970	21
15	104.8	41.7	0.977	22
18	103.4	41.2	0.989	24
23.7	102.3	40.8	1.000	26

^a 50-hp, 1750-rpm, 230-V, three-phase, 60-Hz induction motor.

50% of the full-load kilovolt-amperes (23.7 kvar). These values of kilovars correct the power factor to 0.97 and unity, respectively. Based on 4000 hr/yr operation at 5¢/kWh for electric energy, a correction to unity power factor could result in a saving in energy costs of \$70/yr. The combined motor–capacitor performance at partial loads is shown in Table 4.5. Note that at partial loads with the higher values of corrective kilovars the power factor can be very leading. [Figure 4.7](#) shows the comparison of the corrected

TABLE 4.5 Induction Motor and Capacitor Performance with Power Factor Correction at Various Loads^a

Capacitor kvar	Net power factor				
	Full load	3/4 load	1/2 load	1/4 load	No load
0	0.862	0.852	0.785	0.598	0.073
8	0.931	0.944	0.930	0.865	0.174
12	0.959	0.977	0.981	0.981	0.516
13.7	0.97	0.987	0.994	0.999	0.999
15	0.977	0.993	0.999	(0.996L)	(0.599L)
18	0.989	1.000	(0.995L)	(0.937L)	(0.225L)
23.7	1.000	(0.986L)	(0.935L)	(0.738L)	(0.099L)

^a 50-hp, 1750-rpm, 230 V, three-phase, 60-Hz induction motor.

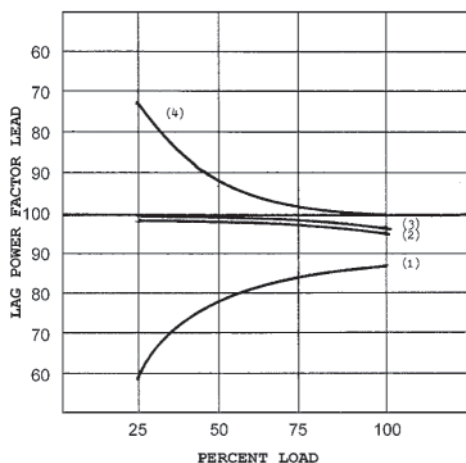


FIGURE 4.7 Power factor of 50-hp induction motor with various levels of kilovar correction: (1) no correction, (2) 12-kvar correction, (3) 13.7-kvar correction, (4) 23.7-kvar correction.

and uncorrected power factor at various level of kilovar correction for the 50-hp induction motor. The high level of power factor correction should be avoided if the motor is going to be operating at partial loads and the capacitors are connected directly to the motor terminals. The application of capacitor kilovars up to the no-load kilowatt-amperes results in a lagging power factor for all load conditions.

The National Electric Code (NEC) has removed any restrictions on the size of power factor correction capacitors applied to induction motor circuits. This places the responsibility on plant electrical engineers to select the power factor correction strategies that best suit their plant operations.

4.4.1 Where to Locate Capacitors

The power factor correction capacitors should be connected as closely as possible to the low-power factor load. This is very often

determined by the nature and diversity of the load. [Figure 4.8](#) illustrates typical points of installation of capacitors:

At the Motor Terminals. Connecting the power capacitors to the motor terminals and switching the capacitors with the motor load is a very effective method for correcting the power factor. The benefits of this type of installation are the following: No extra switches or protective devices are required, and line losses are reduced from the point of connection back to the power source. Corrective capacitance is supplied only when the motor is operating. In addition, the correction capacitors can be sized based on the motor nameplate information, as previously discussed.

If the capacitors are connected on the motor side of the overloads, it will be necessary to change the overloads to retain proper overload protection of the motor. A word of caution: With certain types of electric motor applications, this method of installation can result in damage to the capacitors or motor or both.

Never connect the capacitors directly to the motor under any of the following conditions:

- The motor is part of an adjustable-frequency drive system.

- Solid-state starters are used.

- Open transition starting is used.

- The motor is subject to repetitive switching, jogging, inching, or plugging.

- A multispeed motor is used.

- A reversing motor is used.

- There is a possibility that the load may drive the motor (such as a high-inertia load).

In all these cases, self-excitation voltages or peak transient currents can cause damage to the capacitor and motor. In these types of installations, the capacitors should be switched with a contactor interlocked with the motor starter.

At the Main Terminal for a Multimotor Machine. In the case of a machine or system with multiple motors, it is common practice to correct the entire machine at the entry circuit to the machine. Depending on the loading and duty cycle of the motors, it may be

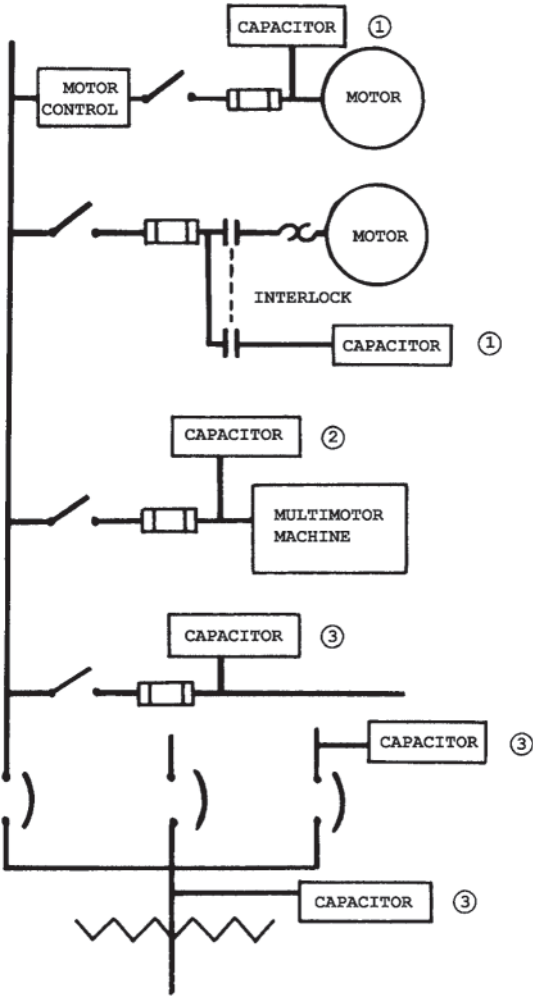


FIGURE 4.8 Where to install power factor capacitors.

desirable to switch the capacitors with a contractor interlocked with the motor starters. In this manner, the capacitors are connected only when the main motors of a multimotor system are operating.

At the Distribution Center or Branch Feeder. The location of the capacitors at the distribution center or branch feeder is probably most practical when there is a diversity of small loads on the circuit that require power factor correction. However, again, the capacitors should be located as close to the low-power factor loads as possible in order to achieve the maximum benefit of the installation.

4.5 THE POWER FACTOR WITH NONLINEAR LOADS

The growing use of power semiconductors has increased the complexity of system power factor and its correction. These power semiconductors are used in equipment such as

- Rectifiers (converters)
- DC motor drive systems
- Adjustable-frequency AC drive systems
- Solid-state motor starters
- Electric heating
- Uninterruptible power supplies
- Computer power supplies

In the earlier discussion about the power factor in sinusoidal systems, only two components of power contributed to the total kilovolt-amperes and the resultant power factor: the active or real component, expressed in kilowatts, and the reactive component, expressed in kilovars. When nonlinear loads using power semiconductors are used in the power system, the total power factor is made up of three components:

1. *Active, or real, component*, expressed in kilowatts.
2. *Displacement component*, of the fundamental reactive elements, expressed in kilovars or kilovolt-amperes.

3. *Harmonic component.* The result of the harmonics and the distorted sinusoidal current and voltage waveforms generated when any type of power semiconductor is used in the power circuit, the harmonic component can be expressed in kilovars or kilovolt-amperes. The effect of these nonlinear loads on the distribution system depends on (1) the magnitude of the harmonics generated by these loads, (2) the percent of the total plant load that is generating harmonics, and (3) the ratio of the short-circuit current available to the nominal fundamental load current. Generally speaking, the higher the ratio of short-circuit current to nominal fundamental load current, the higher the acceptable level of harmonic distortion.

Therefore, more precise definitions of power factors are required for systems with nonlinear loads as follow:

Displacement power factor. The ratio of the active power of the fundamental in kilowatts to the apparent power of the fundamental in kilovolt-amperes.

Total power factor. The ratio of the active power of the fundamental in kilowatts to the total kilovolt-amperes.

Distortion factor, or harmonic factor. The ratio of the root-mean-square (rms) value of all the harmonics to the root-mean-square value of the fundamental. This factor can be calculated for both the voltage and current.

Figure 4.9 illustrates the condition in which the total power factor is lower than the displacement power factor as a result of the harmonic currents.

$$\text{Displacement power factor} = \frac{\text{kW}}{\sqrt{\text{kW}^2 + \text{fund. kvar}^2}}$$

$$\text{Total power factor} = \frac{\text{kW}}{\sqrt{\text{kW}^2 + (\text{fund. kvar} + \text{harm. kvar})^2}}$$

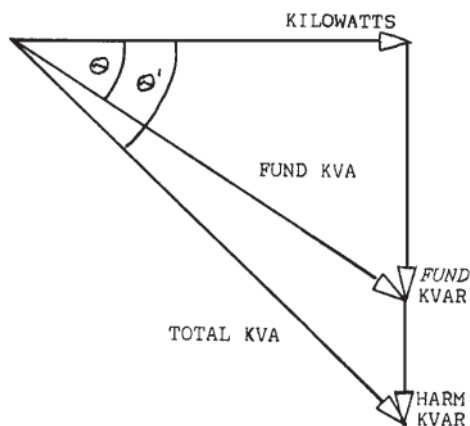


FIGURE 4.9 Power factor, nonsinusoidal system.

Unfortunately, conventional var-hour meters do not register the total reactive energy consumed by nonlinear loads. If the voltage is nonsinusoidal, the var-hour meter measures only the displacement volt-ampere-hours and ignores the distortion volt-ampere-hours. Therefore, for nonlinear loads, the calculated power factor based on kilowatt-hour and var-hour meter readings will be higher than the correct total power factor. The amount of the error in the power factor calculation depends on the magnitude of the total harmonic distortion.

The harmonics result from distorted AC line currents caused by the power semiconductor devices. Typical current wave shapes caused by AC adjustable-frequency drives are shown in Figs. 4.10 and 4.11. Figure 4.10 illustrates the wave shape of the AC line current produced by an adjustable-frequency drive system with the converter section containing silicon control rectifiers (SCRs) or other controllable power switching devices, such as those used in current source inverters and DC drive systems. The harmonic problem for this type of converter is complicated by the voltage notch and voltage spikes that occur during the switching of the converter solid-state devices. The displacement power factor for this type of converter is linear with load. The total power factor and

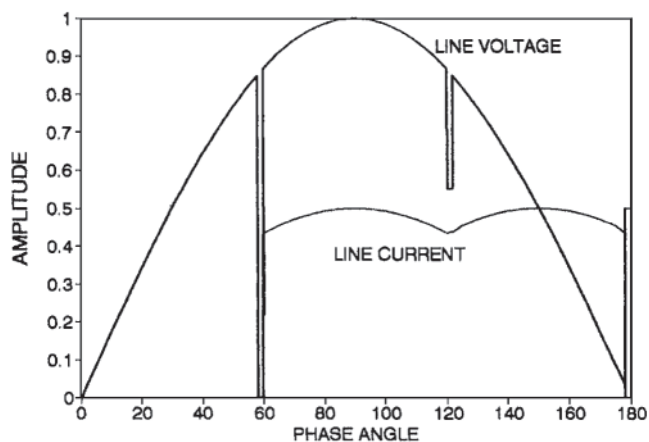


FIGURE 4.10 Typical AC line wave shapes, SCR converter.

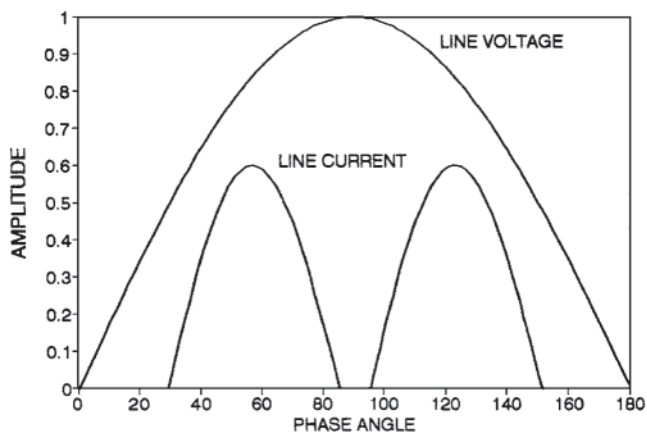


FIGURE 4.11 Typical AC line wave shapes, diode converter.

the harmonic component depend on the system reactance and short-circuit capacity. Figure 4.11 illustrates the wave shape of the AC line current produced by an adjustable-frequency drive system with the converter section operating as a voltage source with a typical diode bridge rectifier converter, such as those used in voltage source and pulse width modulation (PWM) inverters. Again, the total power factor and the current wave shape vary depending on the system impedance, the capacitance on the output of the converter, and the power semiconductor characteristics. The lower the line inductance, the higher the harmonics and the higher the value of the peak current. The displacement power factor for this type of converter is constant over the speed range. However, the total power factor depends on the harmonic distortion factor.

Figure 4.12 compares the displacement power factor for the SCR bridge converter and the diode bridge converter. For both types of converters, there is a difference between the displacement power factor and the total power factor. Again, the total power factor

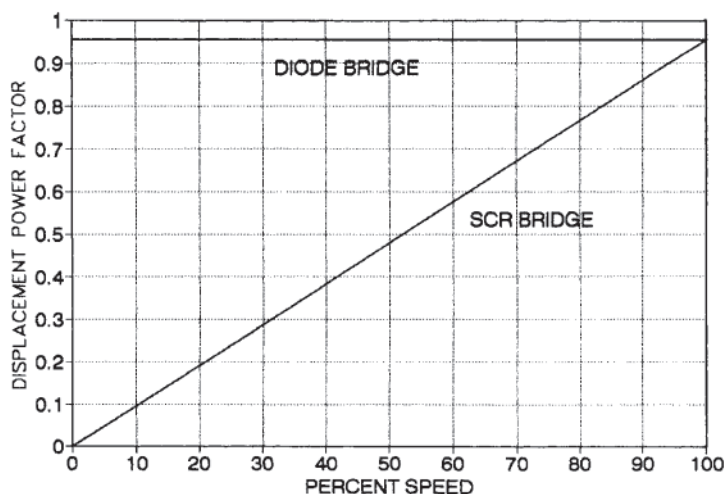


FIGURE 4.12 Comparison displacement power factor diode bridge versus SCR bridge.

depends on the harmonics generated, the harmonic distortion factor, and the power system characteristics.

4.6 HARMONICS AND THE POWER FACTOR

How do you know if you have a harmonic distortion problem?

A single adjustable-frequency drive or DC drive is usually not a problem. However, if over 20% of the plant load contains power semiconductors, there is a good possibility of problems. Some of these problems are

- Transformer overheating and noisy
- Electric motors overheating and noisy
- Power factor correction capacitors overheating or failing
- Unexplained tripping of circuit devices
- Computer malfunctions
- Low system power factor

The application of power factor correction capacitors without an analysis of the system can aggravate rather than correct the problem, particularly if the fifth and seventh harmonics are present.

Since it is not economical to eliminate the harmonics from individual drives or devices, an analysis should be made of the total system to determine the major harmonics present and the methods for reducing the harmonics to acceptable levels. Only then can the proper harmonic filters or traps and power factor correction capacitors be applied at the best location in the system.

The American National Standard, ANSI/IEEE 519–1981 IEEE Guide for Harmonic Control and Reactive Compensation of Static Power Converters, is a guide for making a system analysis. This guide discusses the harmonics generated, the AC line voltage notches, and the harmonic distortion factor. The standard recommends the maximum harmonic current distortion based on the ratio of maximum short-circuit current to maximum load current and suggests locations of harmonic filters. [Table 4.4](#) of the

above standard suggests voltage distortion limits for medium- and high-voltage power systems, and Fig. 27 of the standard shows the theoretical voltage distortion versus short-circuit ratio for six pulse rectifiers. In addition, there are a number of articles in the technical literature that discuss various procedures for determining harmonic distortion and power factor correction, with examples of systems that have been corrected.

A wide variety of instrumentation is available to perform the necessary harmonic analysis of power system or specific load. A few of these are listed below.

- *Harmonimeter*, manufactured by Myron Zucker Inc., Royal Oak, Michigan. This instrument is shown in Fig. 4.13. The unit is battery operated and is quite portable. It is equipped with a clamp-on current transformer, and it measures current harmonics from the second to nineteenth harmonic as a percent of total current. Data in this harmonic range are adequate in many cases. The instrument is easy to use to locate the source of the high-harmonic loads since measurements can be made wherever a clamp-on current transformer can be installed.



FIGURE 4.13 Myron Zucker Harmonimeter. (Courtesy Myron Zucker Inc., Royal Oak, MI.)

- *BMI 3030/3060 Power Profiler*, manufactured by Basic Measuring Instruments, Foster City, California. This instrument is reasonably portable. The unit can measure rms current, voltage, true power, apparent power, true power factor, displacement power factor, and total harmonic distortion. In addition, with the harmonic option package, it can provide a graphic presentation of the voltage or current and an analysis of the harmonics as a percent of the fundamental up to the fiftieth harmonic. Figure 4.14 is a photograph of this instrument. This unit can provide a printout of the voltage and current wave shapes as well as the harmonic spectrum, giving magnitude and phase of each harmonic up to the fiftieth harmonic.
- *Dranetz Disturbance Waveform Analyzer*, Series 656A, manufactured by Dranetz Technologies, Inc., Edison, New Jersey. This unit is also portable. The unit has a cathode display screen and a thermal printer for data output. The unit can measure the harmonic distortion for voltage and current, total harmonic distortion as a percent of the fundamental, and individual harmonics and phase shift of



FIGURE 4.14 BMI 3030/3060 Power Profiler. (Courtesy Basic Measuring Instruments, Foster City, CA.)

each harmonic up to the fiftieth. Figure 4.15 is a photograph of this unit. The following figures illustrate the output capability of this unit. Figure 4.16 is a graphic printout of the phase current for a DC motor drive. Figure 4.17 is the printout of the total harmonic distortion, the odd harmonic contribution, and the even harmonic contribution. In addition, the printout shows the percent and phase angle of each harmonic through the fiftieth. Note that in this example, the major harmonics are the fifth at 33.8% and the eleventh at 8.6%.

4.6.1 System Example

How does this apply to a typical case of a power system with high harmonic content? Consider the case of an industrial plant in which the major circuit has a line current wave shape as shown in Fig. 4.18. This circuit had a mixture of DC drives, adjustable-frequency drives, and standard induction motors. The total current harmonic distortion (THD) was measured at 19.67%, the fifth harmonic at 16.89%, and the voltage harmonic distortion at 4.13%. For comparison, the equivalent rms sine-wave current has been superimposed on Fig. 4.18. After an analysis of the harmonic content of the system, correction equipment was added particularly to reduce the fifth harmonic. Figure 4.19 shows the line current

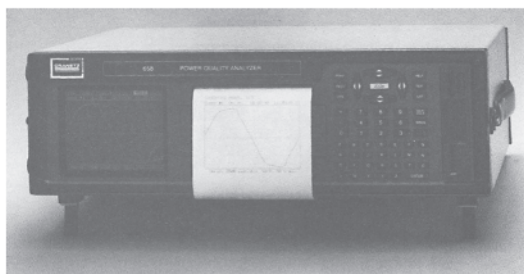


FIGURE 4.15 Dranetz series 656A Disturbance Waveform Analyzer. (Courtesy of Dranetz Technologies, Inc., Edison, NJ.)

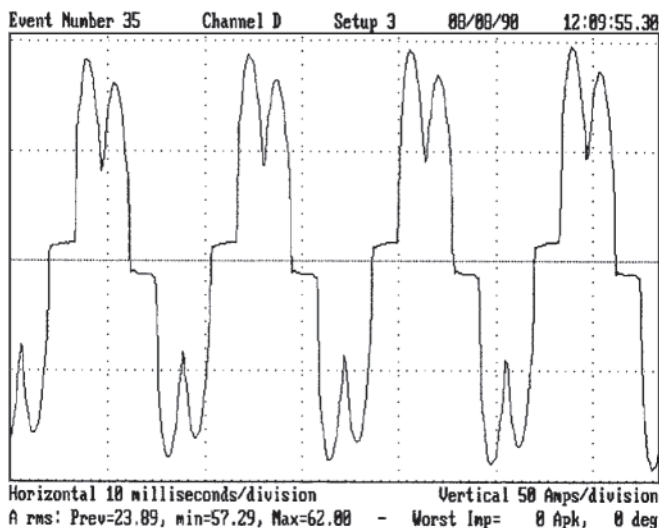


FIGURE 4.16 Current wave shape, DC motor drive. (Courtesy of Dranetz Technologies, Inc., Edison, NJ.)

wave shape after the system correction. Although this doesn't look like a perfect sine wave, the total current harmonic distortion was reduced to 7.92%, the fifth harmonic to 2.79%, and the voltage harmonic distortion to 1.25%. [Figure 4.20](#) is a comparison of the harmonic content before and after correction. The total harmonic current distortion factor of 7.92% is acceptable on many power systems, but the eleventh harmonic of 5.6% may be borderline. If further improvement is required, it would involve reducing the eleventh harmonic.

4.7 POWER FACTOR MOTOR CONTROLLERS

In recent years, solid-state control devices have been developed that, when connected between a power source and an electric motor,

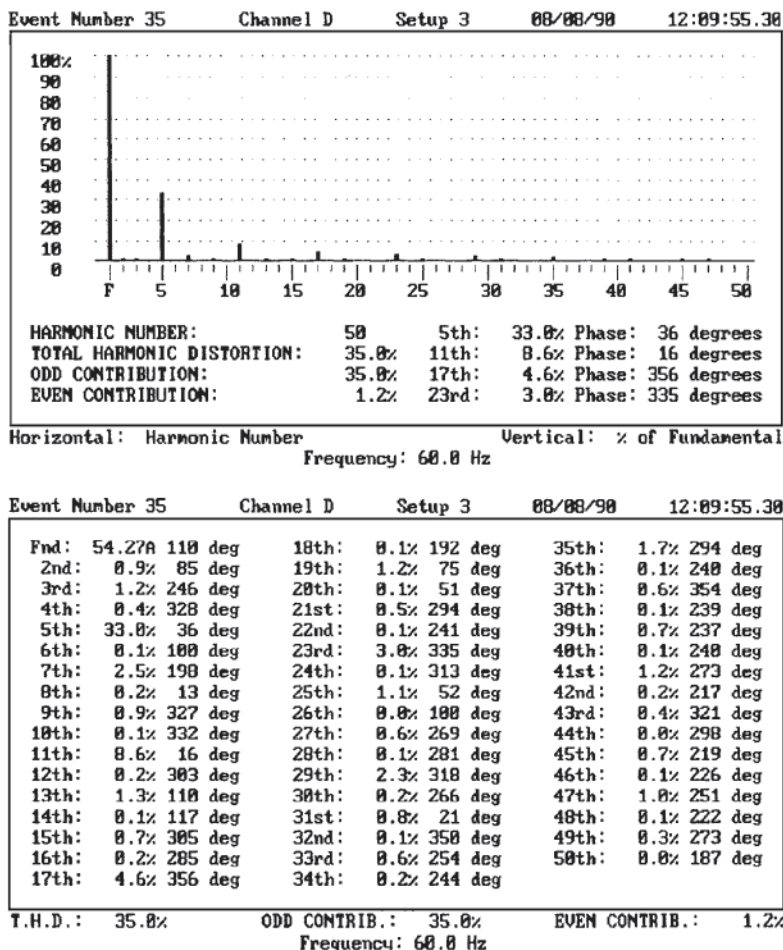


FIGURE 4.17 Graphic and harmonic analysis of current of a DC motor drive. (Courtesy of Dranetz Technologies, Inc., Edison, NJ.)

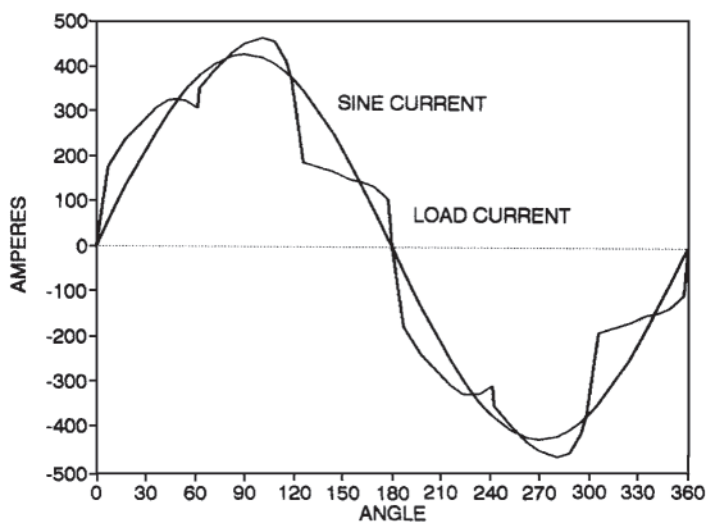


FIGURE 4.18 System line current before harmonic suppression.

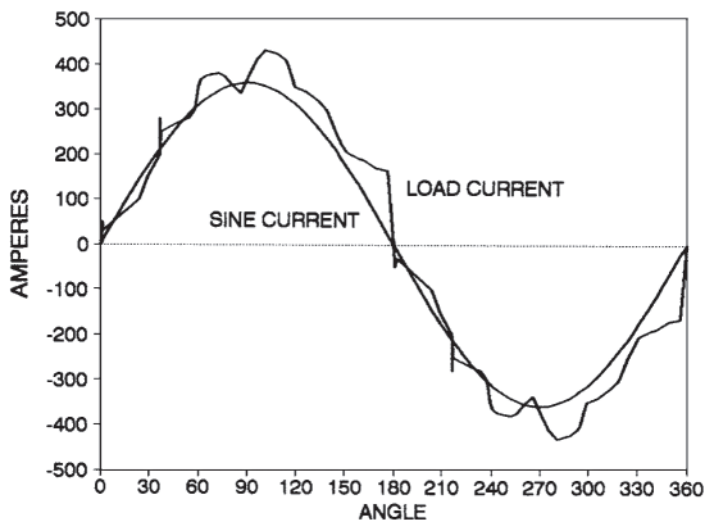


FIGURE 4.19 System line current after harmonic suppression.

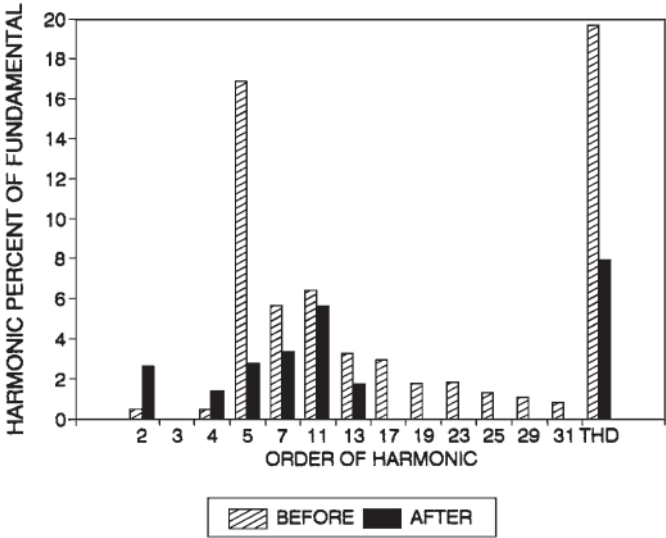


FIGURE 4.20 System harmonic current comparison before and after harmonic suppression.

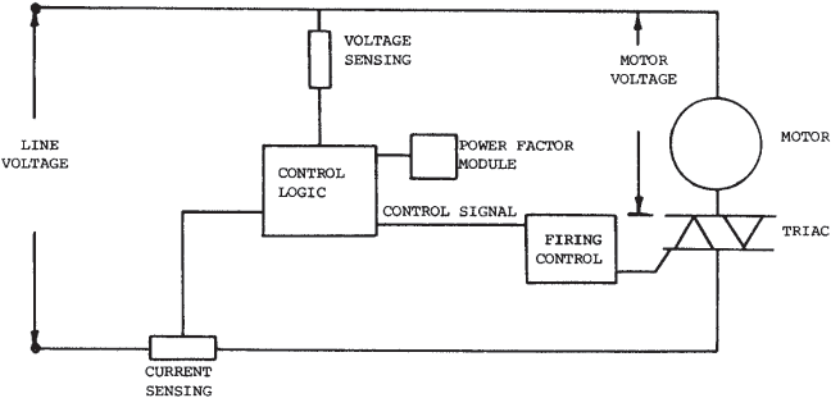


FIGURE 4.21 Single-phase power factor controller block diagram.

maintain an approximately constant power factor on the motor side of the controller. These devices are generally called *power factor controllers*. Most of the units are made under a license of U.S. Patent 4,052,648 issued to F. J. Nola and assigned to NASA.

The controller varies the average voltage applied to the motor as a function of the motor load and thus decreases the motor losses at light-load requirements.

4.7.1 Single-Phase Motors

For application to single-phase motors, the power factor controller consists of a triac, sensing and control circuits, and a firing circuit for the triac, as shown in Fig. 4.21. The power factor controller sensing circuit monitors the phase angle between the voltage and current and produces a signal proportional to the phase angle. This signal is compared to a reference signal that indicates the desired phase angle. This comparison produces an error signal that provides the timing for firing the triac or SCR and causes the phase angle to remain constant when the load changes. Typical motor voltage and current waveforms are shown in Figs. 4.22 and 4.23.

If the phase angle increases, the control circuit adjusts the triac firing angle to decrease the average voltage applied to the motor. Conversely, if the phase angle decreases, the control circuit adjusts the firing angle of the triac to increase the average voltage applied to the motor.



FIGURE 4.22 Single-phase power factor controller with no load on the motor.

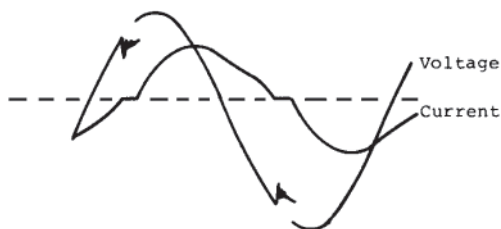


FIGURE 4.23 Single-phase power factor controller with a full load on the motor.

The power factor of the motor is the cosine of the phase angle between the motor voltage and current. Therefore, with this control system, by maintaining the phase angle constant, the motor operates at an approximately constant power factor over the load range. The maximum power factor is the power factor of the motor at the rated load with the triac full on. The minimum power factor will be determined by the minimum voltage setting for no-load operation. This voltage setting must be high enough to provide stable operation and prevent the motor from stalling on the sudden application of load. However, the lower the no-load voltage, the higher the power savings at no load.

How are power savings achieved by decreasing the motor voltage at light loads? The motor losses can be grouped into three categories:

1. Constant losses, such as friction and windage
2. Magnetic core losses, which are some function of the applied voltage
3. I^2R losses, which are a function of the square of the motor current, including rotor losses

For a given load condition, the net losses, and hence the motor power input, decrease with a decrease in voltage as long as the magnetic core losses decrease more than the I^2R losses increase. In addition, there is some increase in losses due to harmonics added to the motor input voltage by the triac switching and the losses in the controller.

In some instances, the increased harmonic content of the input voltage will result in increased motor noise.

The amount of power saved with a power factor controller depends on the duty cycle of the application. Typical power savings under various loads and duty cycles are shown in Fig. 4.24. The power savings are shown as a percent of the full voltage input and as a function of the percent running times at full load versus running at a light load. To result in significant power savings, at least 50%

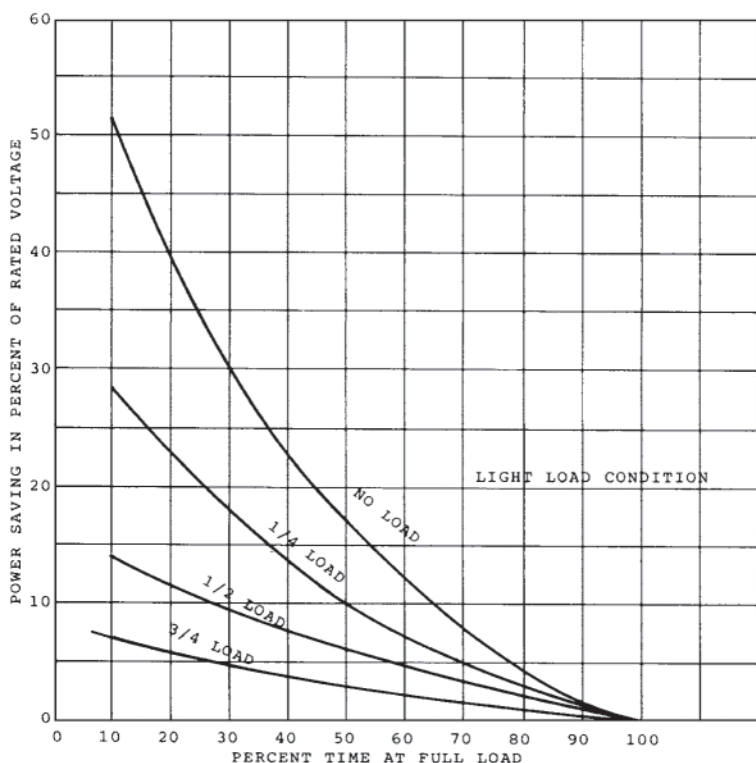


FIGURE 4.24 Single-phase power factor motor controller power savings.

solid-state three-phase motor controllers. These solid-state controllers generally include other features such as current limit, timed acceleration, phase unbalance, undervoltage, and overload protection.

The power factor control function is accomplished by sensing the phase angle between the motor voltage and current. This signal is fed back and compared with a reference, and the difference is used to feed the input signal voltage to the six SCRs in the power module.

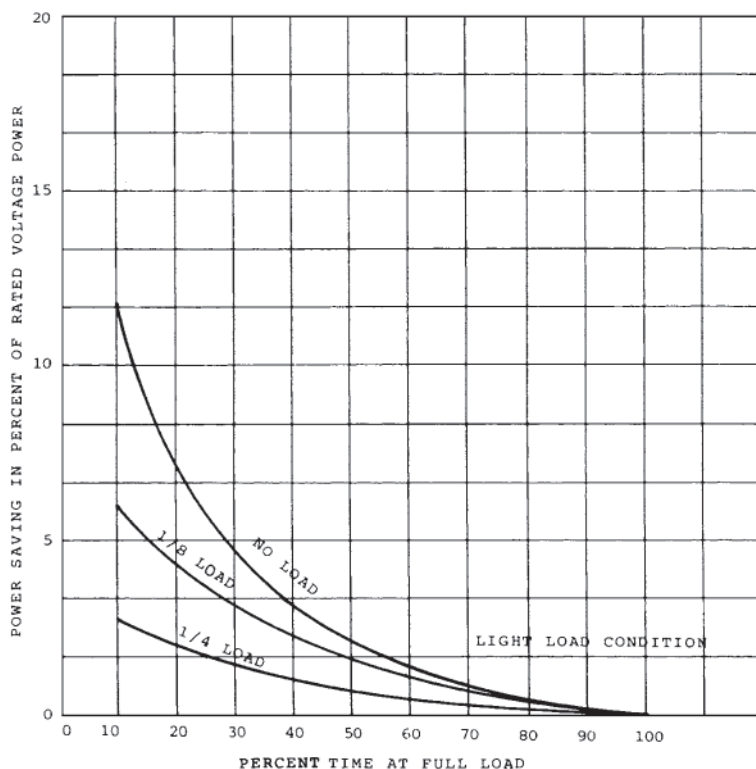


FIGURE 4.26 Three-phase power factor motor controller power savings.

The feedback voltage from the power factor sensing circuit will change the average voltage applied to the motor in accordance with the load on the motor. This reduces both the motor current and voltage under light-load conditions. The circuit is designed to react to load changes to prevent stalling of the motor on instantaneous load changes. Most of the controllers have provisions for setting the minimum no-load voltage; this voltage is generally 65% of rated full voltage. [Figure 4.25](#) is a typical block diagram for the three-phase controller.

The three-phase power factor controllers have potential applications in which the duty cycle for the motor is varying from light or no load to full load as a step function. Examples of potential applications are rip-saws, conveyors, rock crushers, and centrifuges.

The potential power saving when a power factor controller is applied to a three-phase motor is substantially lower than when such a controller is applied to a single-phase motor. [Figure 4.26](#) illustrates the power saving when the controller is applied to a three-phase motor for various duty cycles and loads. These curves depend on the ratio of the no-load losses of the motor. However, it appears that the power factor controller shows significant power savings only on those three-phase motor applications in which the motor operates at no load or light loads over 75% of the operating time.

To apply a power factor controller properly, the load characteristics, motor characteristics, and load cycle must be known. In addition, one must determine how the controller-motor combination will respond to the load cycle. Only then can the potential power saving and economic payback analysis be made.